Impact of Typhoons on the Western Pacific Ocean DRI: Numerical Modeling of Ocean Mixed Layer Turbulence and Entrainment at High Winds

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LONG-TERM GOALS

This study contributes to our long-term efforts toward understanding:
- Mixed layer dynamics
- Processes that communicate atmospheric forcing to the ocean interior

OBJECTIVES

This ongoing collaborative effort is measuring and modeling the response of the upper ocean to strong typhoons both in simple, open ocean conditions and in the more complex conditions caused by ocean eddies and preconditioning by prior storms. The measurement and modeling activities include a focus on the impact of surface waves, air-sea fluxes and the temperature, salinity and velocity structure of the upper ocean. The goals of this effort are to understand key upper ocean processes, test upper ocean models, develop and test new parameterizations of upper ocean physics used and study the feedback from the ocean to typhoon intensity.

APPROACH

The approach of the the modeling component is to use field observations to force Large Eddy Simulation (LES) and upper ocean turbulence models in equivalent numerical cases and to use model-data comparison to test the theoretical basis of mixed layer turbulence scalings and parameterizations. The strategy is to test our physical theories and parameterizations of mixed layer dynamics against data by incorporating them realistically in turbulence-resolving LES models with embedded virtual measurements. Verification of the underlying theories can then be achieved through direct model-data comparison, using observations of ocean waves and turbulence under a wide range of oceanic conditions, and leading to improved parameterizations of upper ocean turbulence. The strong and isolated wind forcing in tropical cyclones provides an ideal environment for testing theories and parameterizations of the role of surface waves in the ocean mixed layer. This follows similar work in CBLAST exploiting the comprehensive view of boundary layer turbulence made possible by the combination of Lagrangian float and EM-APEX measurements. In FY2010 work has concentrated more on developing an improved second moment closure to represent the impact of Langmuir turbulence.

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WORK COMPLETED

During the 2010 field program of this Typhoon DRI, Harcourt has been extensively involved in providing remote sensing imagery, MODIS imagery in particular, to scientists in the field and to the concurrent discussion groups. This has been done by developing and running automatic processing to produce imagery and compact data sets appropriate for download to ships.

Work on LES modeling has included extension of a case set where wind and waves are not directionally coherent to include the rare cases where waves are principally traveling upwind. Other unusual simulations, such as convection in the presence of surface waves, have been run in order to test particular predictions of a new Langmuir turbulence model.
Forcing and case development is ongoing to simulations observed cases from the 2010 field program, and participating in the filed program helps keep these cases realistic.

The most important work done this year is the development and implementation of a second moment closure that more correctly represents the effect of the Craik-Leibovich vortex force terms, due to the interaction of surface wave Stokes drift and Eulerian current shear within the mixed layer. The results section below describes some components of this work that are currently being prepared for publication.

RESULTS

The LES models forced by wind stress and model surface waves via the Craik-Leibovich vortex force can predict mixed layer vertical kinetic energy, vertical velocity skewness and entrainment rates, provided that the surface wave field and drag coefficient are properly specified (Harcourt & D'Asaro, 2008). This understanding has led to the pursuit of a Langmuir turbulence model that is consistent with such LES model results and the observations that they match.

Starting from the work of Kantha & Clayson (2004) that accounted for the increased TKE production due to CL vortex force production, a new model was derived that more correctly treats the impact on model stability functions. What is most unusual about this model is that it predicts that a component of the vertical momentum flux is proportional to the Stokes drift gradient $\partial_z v^S$:

$$\overline{v'w'} = -lq\left(S_M\partial_z\overline{v} + S_M^S\partial_z v^S\right),$$

while the scalar flux retains the form

$$\overline{w'\theta'} = -lqS_H\partial_z\overline{\theta} \ .$$

A down-Stokes-gradient momentum flux component has been hypothesized by McWilliams & Sullivan (2000) and Smyth et al (2002), inferring from LES model results without theoretical grounds. Here, it is the solution to an equilibrium closure model derived from the Reynolds equation for turbulent second moments.

The algebraic equilibrium closure model that forces this assumption predicts that under normal TKE productive conditions the budget of vertical momentum flux covariance is dominated by the product of

$\overline{v'v'}\partial_z v^S$ times a dissipation timescale, and this term cannot be parameterized by the standard down-gradient assumption for momentum flux. Comparisons with steady state LES model solutions show this equilibrium model to be largely correct, neglecting as it does only the transport divergence and planetary rotation terms. The equilibrium model is also what provides algebraic expressions for the stability functions S_H, S_M, S_M^S that then correctly account for the stabilizing and destabilizing effects of CL vortex forcing on eddy diffusivity or, in another sense, on the effective difference between the dissipation and mixing length scales.

The new second moment closure model has been coded into a working column model that provides a substantial improvement to mixed layer shear profiles in high wind cases. It currently adopts the same closure constants used in Kantha & Clayson (2004) for stability functions unaltered by CL forcing, with minimal further assumptions. Aside from tracking down the usual coding errors that bog down such efforts, the only remaining impediment was identifying 'realizability conditions' that prevent physically impossible results like negative TKE components. Model constants and realizability conditions do need further refinement and extensive testing, but the basic model works, as illustrated in Fig. 1, by comparison of the new turbulence model to an LES of mixed layer deepening on the right hand, or resonant side of 2004 hurricane Frances, and to corresponding predictions from the current second moment closure model (Kantha & Clayson, 1994) employed in the Navy's NCOM, NLOM and other ocean models.

The impact on the evolution of SST of including the CL vortex force in such high wind events is relatively small, limited to a fraction of a degree difference during the strongest forcing. This stems in part from the fact that these are some of the youngest seas that can be found in the open ocean, and that therefore Langmuir turbulence is minimized, relative to cases where waves are fully developed. What is more striking however is that including Langmuir turbulence forcing from Stokes drift in an LES (Fig. 1a) largely removes Eulerian current shear from the upper ocean, enhancing levels in the pycnocline. Omitting this from an LES (not shown) produces a result similar to that found using Mellor-Yamada, second moment closure of the variety (Kantha & Clayson, 1994) commonly in use today, with large shear both near the surface and across the mixed layer, and somewhat reduced levels in the pycnocline. The new second moment closure removes this shear and even captures variations in interior shear seen in the LES result as surface forcing drops after day 245.8 and the mixed layer shoals slightly as the sheared pycnocline spreads upward from below.

(a) LES
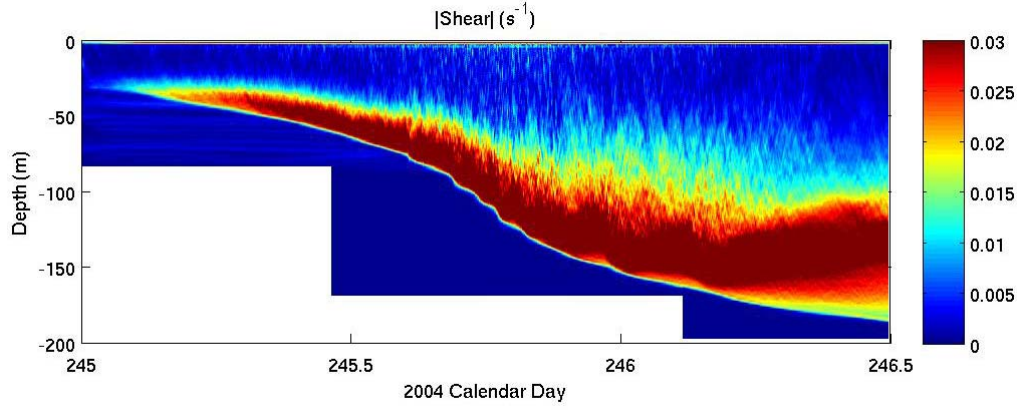
(b) Standard Mellor-Yamada type closure (Kantha & Clayson 1994)
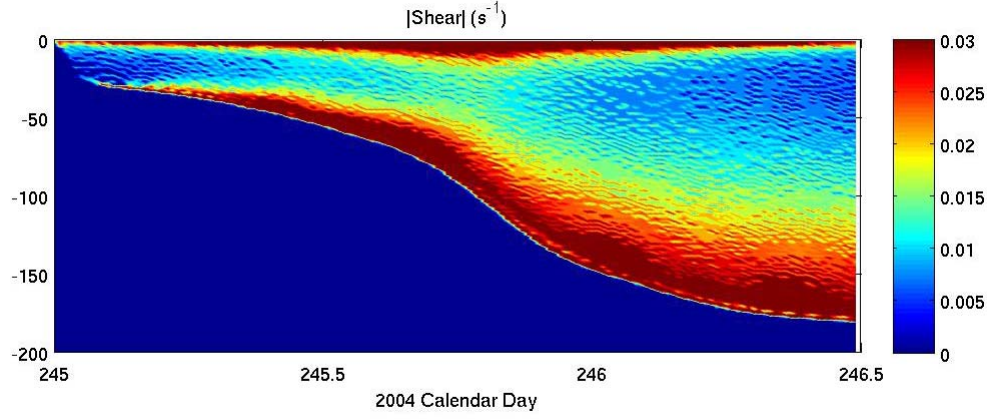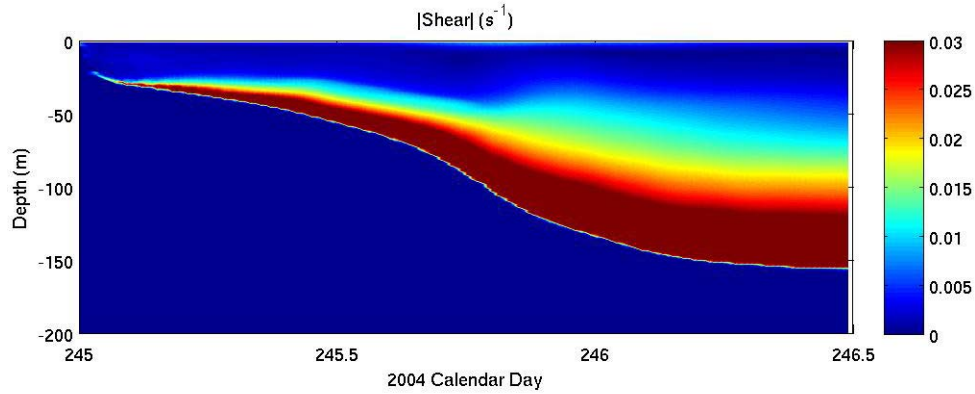

(c) New second moment closure

Fig. RRH1. Upper ocean simulations from the right side of hurricane Frances using (a) an LES model forced by H*winds data and Stokes drift from a wave model; (b) a standard Mellor-Yamada type second moment closure (Kantha & Clayson, 1994) without wave input; and (c) the new second moment closure using down-Stokes-gradient momentum flux, with forcing as in the LES.

In addition to the development of a new second moment closure, LES simulations have been used to further investigate the effect of wind-wave directional incoherence, often encountered in tropical cyclones. Figure 2 shows the effect on mixed layer averaged vertical TKE when the angle between wind and waves is varied through all angles. The LES-based vertical TKE scaling of Harcourt & D'Asaro predicts cases where waves are propagating in the downwind half-plane, but not as well in upwind directions. The root of this departure lies in the effective stratification created when Eulerian and Stokes shear are opposed, resulting in the buildup of a near-surface jet of downwind Eulerian current. TKE production by the increased near-surface shear compensates for part of the damping of Langmuir turbulence by upwind waves. Realizing this and more complex wave-turbulence interactions in an upper ocean mixing model requires the flexibility of a second moment scheme, and will benefit directly from including CL vortex dynamics in the stability functions.
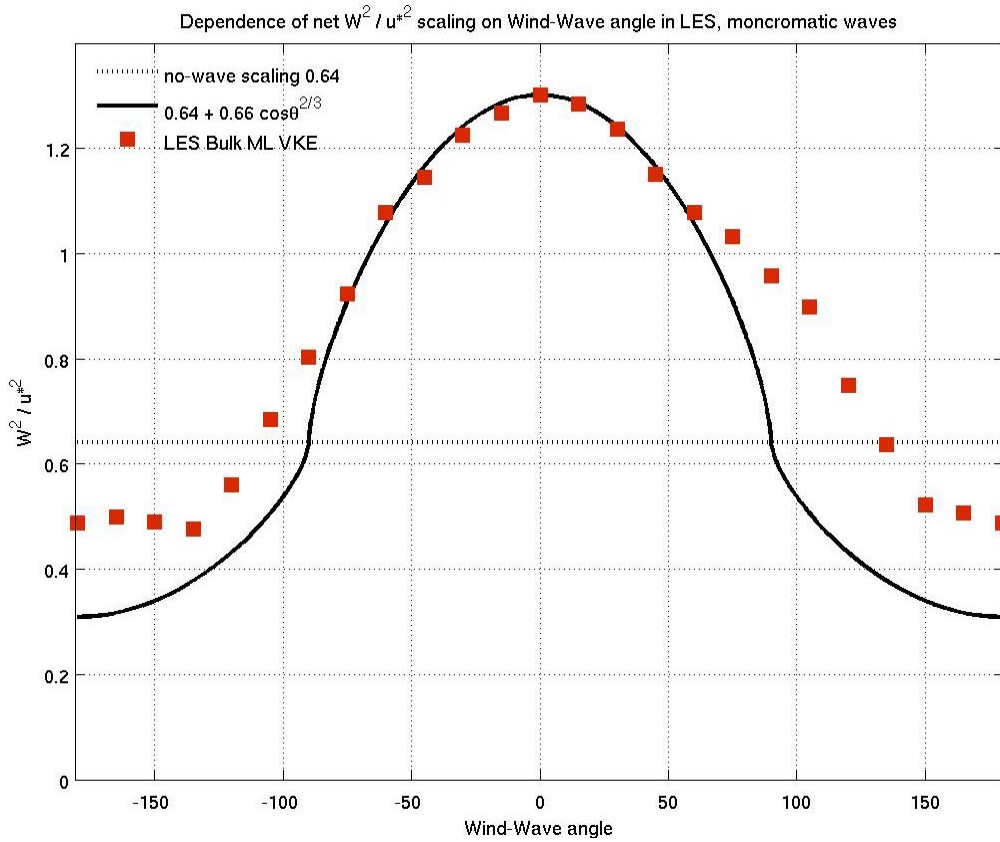

***Fig. 2. Vertical TKE scaling $w^2/u*^2$ for monochromatic wave forcing
cases at varying angles to the wind stress: Solid line parameterizes
the effect of wind-wave angle after Harcourt & D'Asaro (2008).***

Other results for the year include the creation of an automatically updating and customizable system for serving and archiving remote sensing and model imagery and compact data sets for downloading to ships during field programs. Publications include a study of the impact of Lagrangian float buoyancy on turbulence measurements.These corrective prescriptions for turbulence statistics have been applied by D'Asaro, Harcourt & Shcherbina to the Lagrangian float database, and reported on (D'Asaro et al, 2010, Harcourt et al., 2010) at the 2010 Ocean Sciences meeting in Portland, Oregon.There is a clear

signal of the dependence on surface waves in the scaling of vertical TKE on surface wind stress. In addition, there is little evidence in the skewness of turbulent vertical velocity to support the dominance of breaker-turbulence interactions (Sullivan et al., 2007) in setting the level of TKE in the mixed layer. At the 2010 Ocean Sciences meeting in Portland, Oregon, Harcourt also co-sponsored a well-attended session on the role of surface waves in ocean mixed layer dynamics.

IMPACT/APPLICATIONS

Surface waves are believed to play a key role in the upper ocean boundary layer, yet do not appear explicitly in any of the major boundary layer parameterizations used in ocean circulation or climate models. Addressing this defect will lead to mixed layer models with turbulence intensity and entrainment efficiency, scaled by wind stress, that increase with surface wave age, in the presence of swell. While subsurface shear may dominate pycnocline mixing under inertially resonant wind forcing conditions, variability in mixed layer energy due to surface waves will play a significant role in deepening the layer when this is not the case. A boundary layer model that includes sea state dependencies, in addition to the usual dependencies on surface stress, buoyancy flux, and subsurface shear, will ultimately be more accurate than one which does not.

RELATED PROJECTS

Typhoons DRI continues previous work in the Hurricane component of CBLAST DRI. Development of the field program system for archiving and serving images and compact data to ship science parties has been done in conjunction with work in the LatMix DRI.

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